

High resolution x-ray microtomography based micro finite element analysis of mechanical properties of cellular material

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Abstract

The macroscopic mechanical (elastic) properties of closed foams (ROHACELL) estimated from micro finite element analysis are reported in this paper. The complex 3D geometries of ROHACELL foams with different densities were analyzed using high resolution X-ray microtomography (HRXMT). The microstructures obtained from HRXMT are converted to hexahedra mesh for analysis using the micro finite element method (microFE). Major steps for finite element analysis using “FEBio” coupled with HRXMT data are summarized as follows:

- Pre Processing (VGrid) – Meshing and elemental properties assignment.
- PreView – Mesh editing and setting up – material, boundary condition, model, simulation parameters.
- FEBio (Finite Elements for BioMechanics) - Run FE simulation.
- PostView - View simulation and post processing.
- Validation – Comparison with results from experimental compression tests.

The relationship between mechanical properties and relative density was investigated and validated with experimental results from compression tests. The elastic stress-strain curves simulated using the microFE method compare very well with the experimental results.

The methodology involving the coupling of 3D microCT data with microFE analysis allows for modeling the mechanical properties of similar microstructures to design, produce, and optimize the performance of engineered cellular material.

Keywords: X-ray Microtomography, Micro Finite Element, Cellular Material, Elastic Behavior

1. Introduction

Polymer foams, for specific example polymetahcrylimide (PMI) or ROHACELL (brand name), consist of a substantial amount of porosity which leads to very low density, on the order of 0.1 g/cm³. Besides the light weight of the foam material, the ROHACELL also provides very unique material properties such as very high specific strength, specific energy absorption, and acoustic damping. ROHACELL has been used in many interesting applications and is frequently used as the core for composite layered structures.

Two important parameters, namely the microstructure of the foam and the properties of the polymer wall material have a significant influence of the mechanical properties of the foam. Modeling the mechanical properties of ROHACELL microstructures will provide important data to design, produce, and optimize the performance of engineered cellular material.

Both analytical and experimental studies have been reported in the literature for the estimation of the macroscopic mechanical properties of closed foams (ROHACELL) based on their density [1,2]. In this paper, the micro finite element (microFE) method is used to model the macroscopic elastic properties of closed foams. In this regard, the complex 3D geometries of ROHACELL foams with different densities were analyzed using high resolution X-ray microtomography (HRXMT). The microstructures obtained from HRXMT are converted to hexahedra mesh for compression simulation using the micro finite element method (microFE). Major steps for finite element analysis using “FEBio” [3] coupled with HRXMT data are discussed in detail. The relationship between mechanical properties and relative density was investigated and validated with experimental results from compression tests. The methodology involving the coupling of 3D microCT data with microFE analysis

allows for modeling the mechanical properties of similar microstructures to design, produce, and optimize the performance of engineered cellular material.

2. Characterization of ROHACELL Foams

Table 1 lists the measured density (ρ^l) of ROHACELL samples (RC 31 IG, RC 51 IG, RC 71 IG, and RC 110 IG) compared to the results (ρ^*) from Maiti's work [1] and the density of cell wall material (ρ_s).

Table 1. Densities of ROHACELL foam samples.

Samples	ρ_s (kg/m ³)	ρ^l (kg/m ³)	ρ^* (kg/m ³)	Solid % by Volume
RC 31 IG	1200	41.2	34.0	3.43
RC 51 IG	1200	50.7	51.6	4.23
RC 71 IG	1200	72.1	70.4	6.00
RC 110 IG	1200	95.4	124.0	7.95

ρ^l : measured ρ^* : Maiti's work [1]

2.1. 3D image acquisition by high resolution x-ray microtomography (HRXMT)

High Resolution X-ray microtomograph (HRXMT) is a unique instrument with excellent capabilities for the 3D characterization of internal structures in a nondestructive manner [4]. Four ROHACELL samples were analyzed by HRXMT.

ROHACELL specimens (closed cell foam with size of about 8 x 8 x 8 mm) were prepared for HRXMT scans using the HRXMT facility (Xradia's MicroXCT-400). Operation parameters for the HRXMT scans are summarized as follow: 40 KV, 4X lens, 10 second exposure time, 150 μ m glass filter, 1000 projected views, and 5.77 micron reconstructed resolution.

2.2. 3D microstructure of ROHACELL foams

Fig. 1 presents 2D slice, and split 3D volume rendering images for the ROHACELL samples (RC 31 IG, RC 51 IG, RC 71 IG and RC 110 IG). The 3D image consists of 992x1005x970 voxels. The size of each voxel is 5.77 x 5.77 x 5.77 μ m.

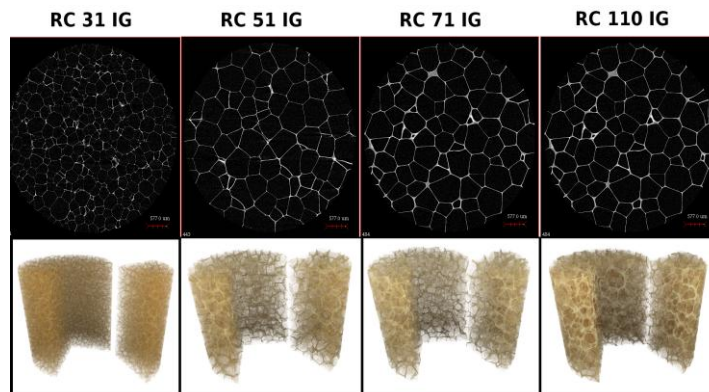


Fig. 1. 2D section images (upper), and split 3D volume rendering images (bottom), of samples ROHACELL (RC 31 IG, RC 51 IG, RC 71 IG and RC 110 IG).

2.3. 3D closed cell size distributions for ROHACELL samples based on the watershed algorithm

Watershed algorithm [5] was used to patch the broken cell walls and to determine the 3D closed cell size distributions. Fig. 2 shows the volume rendering images for the separated cell sizes of ROHACELL foams. The measured cell size distributions of ROHACELL foams are shown in Fig. 3.

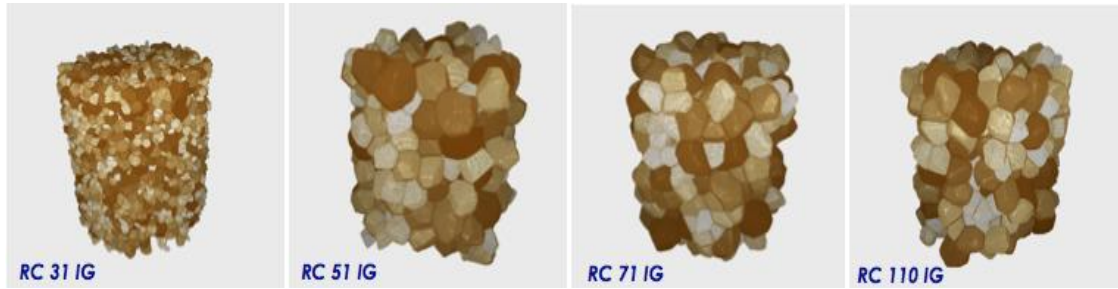


Fig. 2. 3D volume rendering images of the separated cell size of ROHACELL samples (RC 31 IG, RC 51 IG, RC 71 IG and RC 110 IG) from 3D-image analysis using a 3D-watershed algorithm from HRXMT scans (5.77 μm resolution).

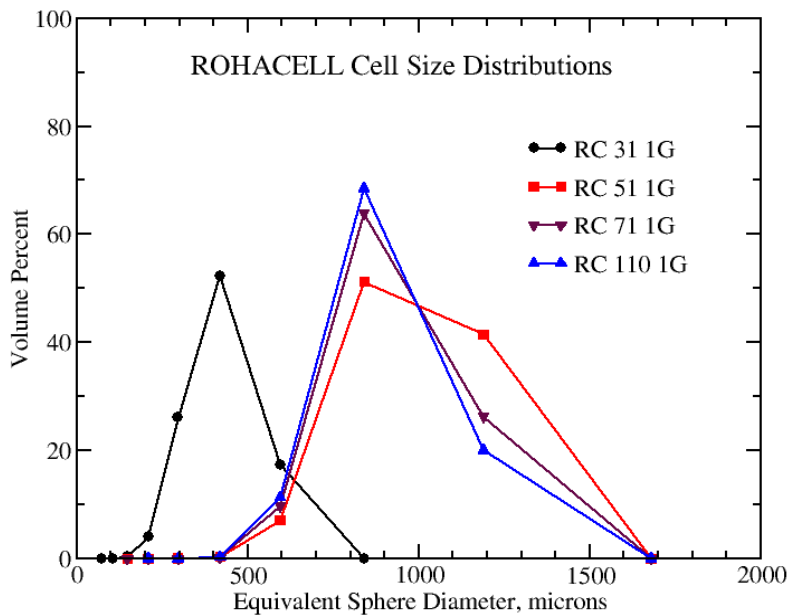


Fig. 3. Measured 3D closed cell size distributions from Fig. 2 for ROHACELL samples (RC 31 IG, RC 51 IG, RC 71 IG and RC 110 IG).

3. Modeling the Mechanical (Elastic) Property of ROHACELL

3.1. Modeling of mechanical (elastic) properties

The microstructures obtained from HRXMT are converted to hexahedra mesh for compression simulation using the micro finite element method (microFE). The relationship between mechanical properties and relative

density was investigated and validated with experimental results from compression tests. Major steps for finite element analysis using “FEBio” [3] coupled with HRXMT data are as follows:

The reconstructed volume images of foams from HRXMT analysis consist of voxels (volume elements) which can be converted to hexahedra volume mesh easily. In this regard, the SimBio-VGrid mesh generator [6] is used to convert 3D CT data to hexahedra mesh. Before meshing, as mention previously, the broken cell walls were patched for cell size measurement and to prevent difficulty during FE analysis due to dangling elements. Further, adequate volume size with a sufficient number of elements to represent the complex geometry of foams is necessary for numerical simulation. In this regard, more than 5 cells are recommended in the literature [7]. For further discussion and comparison of FE analysis of cellular materials based on different type of elements, such as tetrahedral or shell, the reader is referred to the literature [8] and the cited references. The microFE analysis software, FEBio [3], was used for the modeling the mechanical properties of ROHACELL foams. In general, finite element analysis consists of pre-processing and post-processing. PreView (pre-processing software of FEBio) was used to setup material property, boundary condition, model, and simulation parameters. Fig. 4 shows the parameters setting for compression simulation of ROHACELL mesh during pre-processing using PreView.

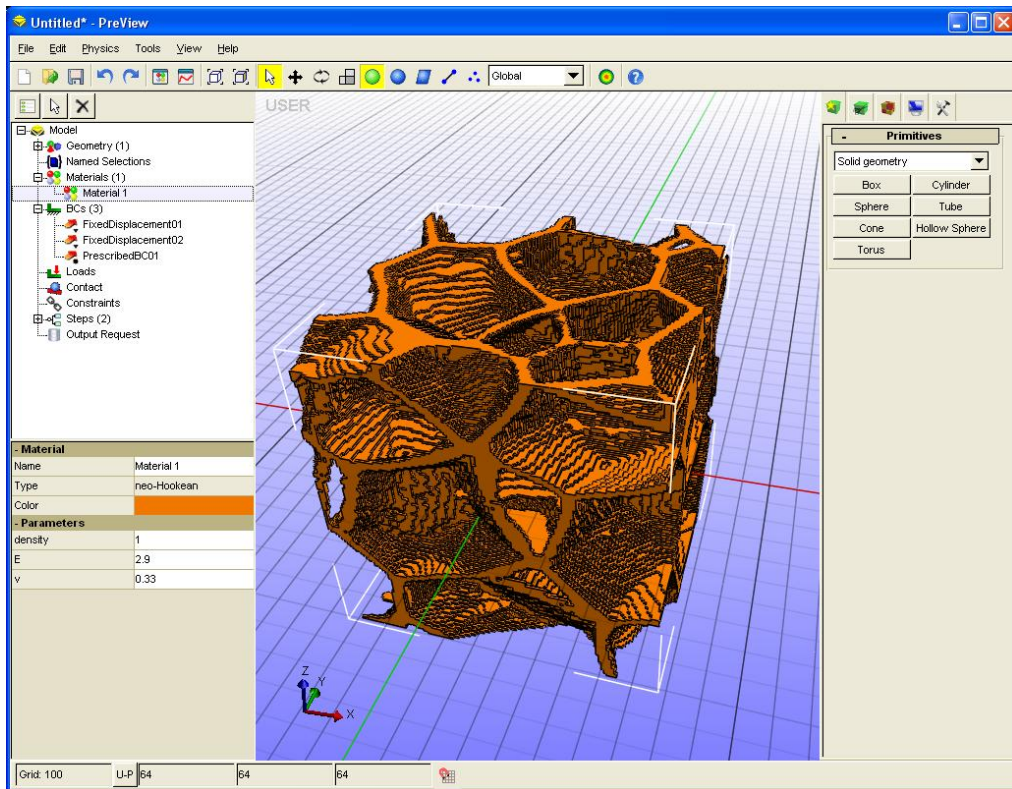


Fig. 4. Parameters setting for compression simulation of ROHACELL mesh during pre-processing using PreView.

3.2. Compression simulation - FEBio

Uni-axial compression tests were simulated using FEBio. The following parameters were set for the numerical simulations: Young’s modulus $E = 2.9$ GPa, Poisson’s ratio $\nu = 0.33$, and 10 time steps to 5% compression. Fig. 5 shows 3D views of the simulation of foam (RC51, 256x256x256 voxels) undergoing compression (0%, 1.83% and 5.0% compressive strains). The nodes of the material are shaded according to their effective (von Mises) stress in GPa.

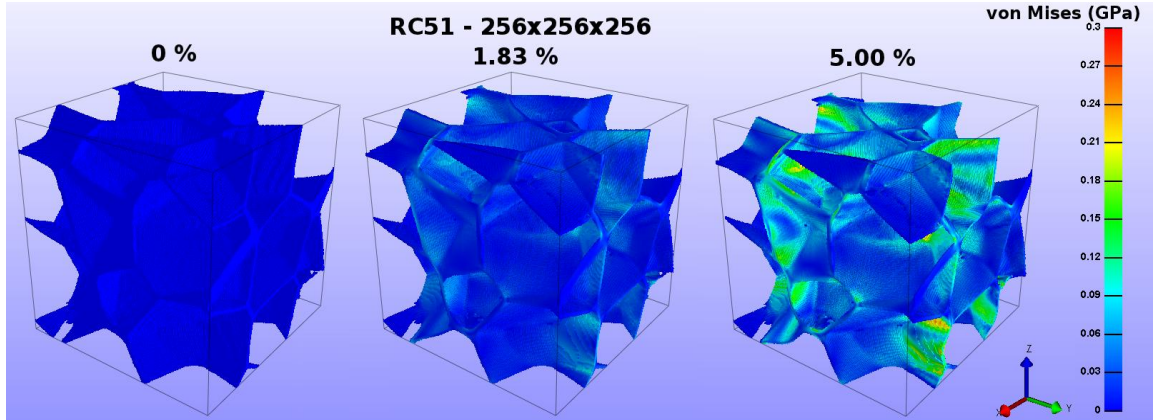


Fig. 5. 3D views of foam (RC51, 256x256x256 voxels) in compression (un-deformed, at 1.83% compressive strain, and 5.0% compressive strain) from FEBio simulation using PostView. Color bar indicates the effective (von Mises) stress (GPa).

3.3. Validation with experimental compressive load and deformation

Compressive load is simulated by 10 time steps of nodal displacement to 5% in the Z-direction. To evaluate the compression simulation, first, the nodal reaction force inside the loaded surface as shown in Fig. 6, are summed up. Then, the macroscopic engineering stresses (σ) are obtained as,

$$\sigma = \frac{\sum F_n}{A} \quad (1)$$

where F_n is the nodal reaction force, summed upon the loaded surface, and A is sum of the initial loaded surface area. The engineering strains are defined as the average displacement (u) of the nodes inside the loaded surface divided by the initial height (h) of the specimen,

$$\varepsilon = \frac{u}{h} \quad (2)$$

Young's modulus is calculated as,

$$E = \frac{u}{\varepsilon} \quad (3)$$

The solid line in Fig. 7 shows the stress-strain curve obtained from the compression tests on a cylindrical sample of RC 51 foam. Results obtained from numerical simulations at two sizes (200x200x200, and 256x256x256 voxels) using FEBio are also included in Fig. 7 for comparison. The experimental modulus was 28.1 MPa while the simulations moduli were 29.2 MPa at 200 voxel size and 30.5 MPa at 256 voxel size. Excellent agreement between experiment and simulation based on HRXMT and FEBio was obtained.

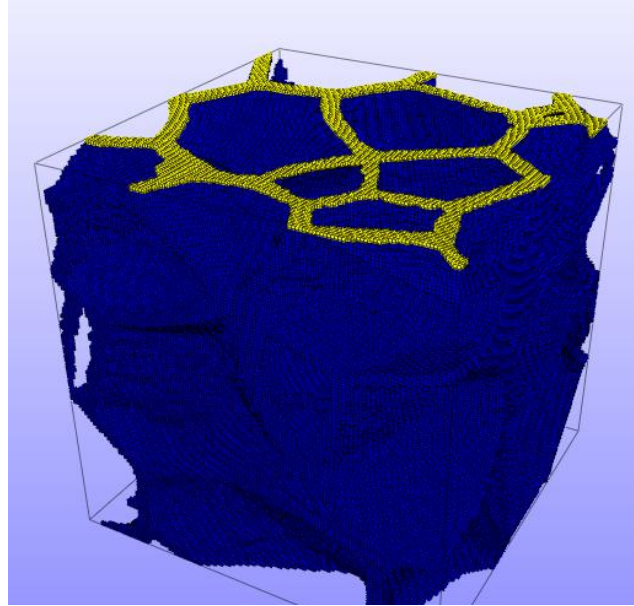


Fig. 6. Loading surface (yellow) for the calculation of nodal reaction force.

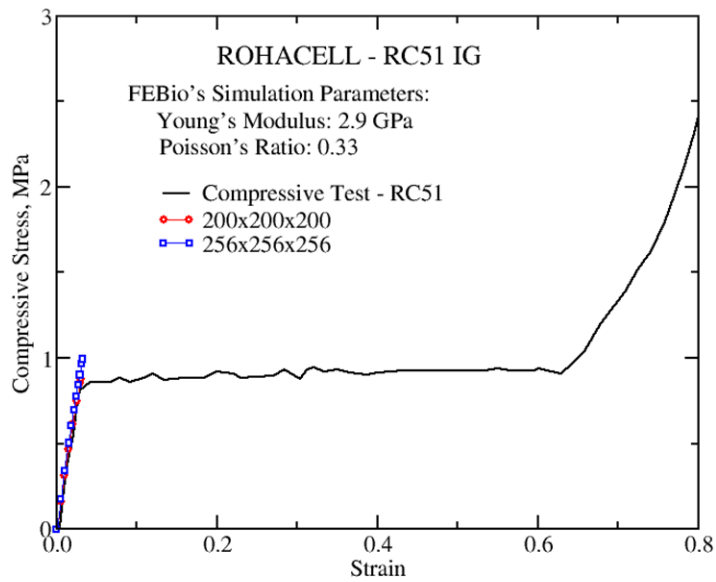


Fig. 7. Comparison of stress-strain curves (linear elastic region) obtained from numerical simulation using HRXMT and FEBio with experimental data (ROHACELL RC 51 IG).

Table 2 shows the numerical compressive simulation results obtained from four ROHACELL foams (RC 31, RC 51, RC 71 and RC 110) and compared with the experimental compression test from Maiti's work [1].

Table 2. Comparison of Young's Modulus (E^*) between the numerical compressive simulation using FEBio and Experimental compression from Maiti's work [1] of four ROHACELL foams.

Samples	E^* (MPa)	E^* (MPa) - FEBio Simulations		
	Maiti's work[1]	128x128x128	200x200x200	256x256x256
RC 31 IG	20.8	23.96	-	-
RC 51 IG	28.1	-	29.2	30.5
RC 71 IG	56.9	-	35.7	49.9
RC 110 IG	129.7	-	-	70.6

As mentioned previously, adequate volume size with a sufficient number of elements to represent the complex geometry of foams is necessary for numerical simulation. For example, due to the insufficient volume size, a lower modulus was obtained at 200 voxel size for RC 71 foam. Besides the insufficient number of elements, density variation of foams may cause the difference between the modulus from simulation of RC110 foam and from Maiti's work [1]. In this regard, as indicated in Table 1, the measured density (ρ^1) is 95.4 kg/m^3 for RC 110 samples which is significantly lower than the measured density ($\rho^* = 124 \text{ kg/m}^3$) reported in Maiti's work [1].

4. Conclusions

In this paper, the macroscopic mechanical (elastic) properties of ROHACELL foams are reported. The methodology involving the coupling of 3D microCT data with microFE analysis allows for modeling the macroscopic mechanical properties for microstructures of engineered cellular material.

The relationship between mechanical properties and relative density was investigated and validated with experimental results from compression tests. The elastic stress-strain curves simulated using the microFE method compare very well with the experimental results.

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